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Busek Co. Inc.
Natick, Massachusetts, USA

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PERFORMANCE OF AN 8 kW HALL THRUSTER

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Abstract

For the purpose of either orbit raising and/or repositioning, the Hall thruster must be capable of delivering sufficient thrust to minimize transfer time. This coupled with the increasing on-board electric power capacity of military and commercial satellites, requires a high power Hall thruster that can provide high thrust for orbit transfer in addition to high Isp for station keeping.

To satisfy these requirements, Busek Co. embarked on the development of a novel, high power Hall thruster, capable of efficient operation over a broad range of Isp and thrust. We call such a thruster the bi-modal Hall thruster. For bi-modal operation the thruster, while operating at constant power, should deliver continuously increasing thrust with decreasing Isp. Ideally, the Isp ratio of the two modes should exceed two.

The Busek Co. Inc., in a SBIR program sponsored by the Air Force Research Laboratory (AFRL) designed, constructed and tested an 8 kW thruster and associated high power cathode designated BHT-8000 and BHC-500, respectively. The thruster/cathode assembly was successfully tested in its baseline configuration in Busek's cryogenically pumped (T8) test facility. This paper describes the performance of that thruster, paying particular attention to the plasma behavior outside the discharge cavity. At 8 kW and 300 V discharge the thruster delivered 512 mN thrust at 63.5% anode efficiency and 2024 sec anode I_{sp}.

A simple performance predicting model, applicable to all sizes and types of Hall thrusters also is presented. It adequately correlates the measured thrust and Isp expressed in terms of two loss parameters, primary electron and voltage loss. External plume measurements, together with the model and visual observations, suggests that the plasma downstream of the discharge of an efficient performing thruster forms at its center a high luminescent and conductive cone on the thruster axis of symmetry.

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Introduction

In recent years, there has been an increase in the interest of electric propulsion, in particular for satellites intended for communication purposes. The beneficiary of this trend has been the Hall effect thruster, that combines the attributes of low cost and complexity, high efficiency and optimum specific impulse for most missions.

In 1992, Busek began the development of a totally domestic source of Hall thrusters, that were only available from Russian suppliers at the time, and still today, Busek (and our licensee Primex Aerospace Co.) are the only suppliers of Hall thrusters that have not relied on Russian technology, patents and know-how.

Several types of Hall thrusters, ranging in nominal power input from 150 W to 8 kW have been developed. A sample of these thrusters are shown in Fig. 1. Starting from the top, pictured are our nominal 200 W Tandem Hall thruster,[1] a non-circular, nominally 3 kW thruster with a racetrack shaped discharge designated BHT-RT-3000 and our nominal 8 kW thruster. This paper describes the results of the largest device, the 8 kW, designated BHT-8000.

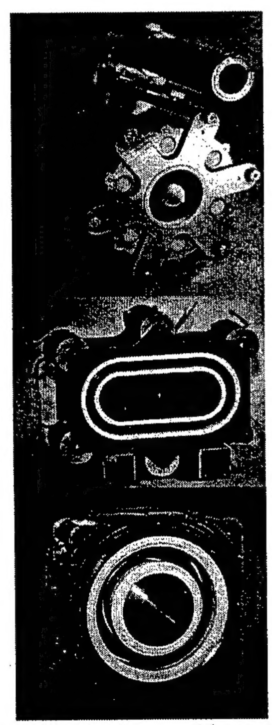

Fig. 1 Busek is developing, with government and private funding, several types of Hall thrusters ranging from 150 W to 8 kW

Although each thruster has a distinctly different internal design, the performance of each can be well described[2] by a simple parametric model and correlated to the visual behavior of plume downstream of the exit plane.

The typical Hall thruster is shown schematically in Fig. 2 that also illustrates the ionization and acceleration processes. Although familiar to the community, the principles of operation are described for completeness.

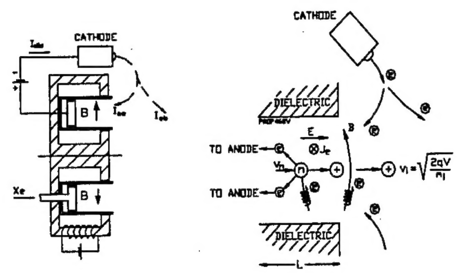

Fig. 2 Cross-sectional schematic of a typical Hall thruster detailing the ionization and ion acceleration process

The Hall thruster is an axisymmetric device, that contains an annular cavity where a plasma is created by passing a current between the positive polarity electrode and an externally located cathode. The plasma gas, typically xenon, is uniformly distributed at the upstream end of the discharge cavity, frequently through propellant injectors located within the anode. A primarily radial magnetic is applied across the end of the discharge by either permanent or electromagnets. As the neutral gas proceeds at thermal speed through the cavity, they encounter a zone of high electron density. These electrons have been greatly slowed by the high radial magnetic field by forcing them to execute gyromotion around the field lines.

FIELD?

Due to the mild collisionality, the electrons execute mostly **E** x **B** azimuthal drift around the annulus. Due to this drift, the electron azimuthal flow can be 100 to 200 times that of the mean axial current, hence creating a high Hall parameter ($\beta \sim J_\theta / J_z$). The high azimuthal current density creates a high axial electric field and leads to a high rate of neutral ionization. The ions, created by collisions of the neutral propellant and electrons, are only weakly affected by the radial magnetic field and are accelerated solely by the applied electric field. Since the plasma density is low, the ions are accelerated to an exit velocity c_i as given by the expression

$$c_i = \sqrt{\frac{2eV_a}{m_i}} \qquad [1]$$

where V_a is the ion accelerating voltage and m_i is the ion mass. The high ion exit speed, and good propellant utilization (η_u) (in a good thruster 90% of the flow is transported by ions) combines to give the Hall thruster a high specific impulse (1600-2000 sec) as shown by the expression

$$I_{sp} \cong \frac{\eta_u c_i}{g_o} \qquad [2]$$

where g_o is the gravitational acceleration, and propellant utilization defined as the mass flow rate of ions $\dot{m}_i$ divided by the total mass flow to the thruster $\dot{m}_t$.

The presence of electrons within the entire discharge chamber creates plasma neutrality and no space charge limitation arises in this type of thruster. This allows Hall thrusters to operate with significantly higher thrust density when compared to conventional ion engines.

Thruster Description

There are a number of basic criteria that can be derived and applied to the design and/or scaling of a Hall thruster. The approach used at Busek and elsewhere[3] involves a methodology based on the relationship of the thruster characteristic length (L) to the ion Larmor radius (ρ_i), the electron Larmor radius (ρ_e), and ion-neutral mean free path (λ) defined as,

$$L > \rho_e = \frac{m_e \upsilon_e}{qB} \quad L << \rho_i = \frac{m_i \upsilon_i}{qB} \quad L < \lambda \approx \frac{1}{n_n Q_{in}} \qquad [3]$$

where υ is the velocity for the electrons and ions as denoted by the subscripts.

To maintain constants ρ_e, ρ_i, λ and υ requires

neutrals?

$$n_n \sim n_i = n_e \sim \frac{1}{L} \qquad I_{dis} = n_i \sigma_i qA \sim \left(\frac{1}{L}\right)(L)^2 \sim L$$

$$B \sim \frac{1}{L} \qquad J_{dis} = I_{dis} / A \sim \frac{1}{L} \qquad [4]$$

$$V_{dis} \sim \text{invariant} \Rightarrow \mathrm{E} \sim \frac{1}{\mathrm{L}} \qquad \text{Power} = V_{dis} I_{dis} \sim L$$

- dis (subscript) is discharge? (not def'd til pg 5)

This approach to scaling involves maintaining the ratio of the mean free path for each particle to the thruster characteristic length approximately constant. The challenge for high power thruster design is dictated by increased collisionality, that requires the ion-neutral collision mean free path must be greater than the acceleration (λ>L). Otherwise, the neutrals interfere with the ion acceleration and the whole plasma behaves as a coupled fluid with lower specific impulse.

Therefore, to avoid plasma thermalization and maintain high thrust density requires careful management of the axial magnetic field profile that dictates L. To minimize (L) requires the axial gradient in the radial magnetic field be increased. Therefore establishing the limiting value for the particle number densities is a key design issue for high power thrusters.

Once the thruster characteristic dimension (L) and the plasma parameters are determined they are related to the discharge zone geometry thus bridging the relationship of plasma properties to thruster geometry.

The key features of the 8 kW design are embodied in the patent pending[4] innovative discharge chamber. It employs a unique combination of features that contribute to its high performance. Some of the features are the combination of conductive/magnetic and dielectric materials within the discharge chamber housing, a unique method of propellant injection and anode shape/geometry. This is combined with control of the magnetic field distribution using a combination of four external coils and an independently powered central coil. This arrangement contributes to a short acceleration zone and aids in focusing the discharge plume such that the majority of the ions exit the thruster parallel to the thruster axis of symmetry. The result is a thruster with low losses (i.e. high efficiency), long life and low plume divergence.

The magnetic structure serves the dual purpose of the structural body for the thruster, conducting the field created by the electromagnets and guiding it across the radial gap between the inner and outer magnet poles. The magnet conductors have low flux levels, allowing the use of low cost magnetic iron having high permeability and saturation flux density. The structure consists of a back plate, central stem and inner front pole, the outer cores and downstream (outer pole) flange.

A ground screen is used to prevent electron migration to the external surfaces of the discharge chamber and propellant isolators are used to isolate the propellant feed system from the anode/chamber.

The design specifications for the 8 kW thruster and the principle operating parameters resulting from our design analysis are listed in Table 1. As will be shown in the subsequent section, the measured performance exceeded the design predictions.

Table 1
Predicted Operating Parameters and Design Specifications for the BHT-8000

Power Input	8266 Watts
Discharge Voltage	300 V
Discharge Current	27.55 A
Beam Current	22.61 A
Mass Flow	30 mg/sec
Thrust	563 mN
Efficiency	61.3%
Specific Impulse	1837 sec
Discharge Cavity Mid. Dia.	170 mm
Thruster Envelope H x W x D (Cathode Excluded)	240 x 240 x 110 mm
Thruster Weight	~20 kg

Cathode Description

One important aspect of producing a stable plasma and efficient Hall thruster operation is to provide a cathode capable of delivering the very high currents required for a broad range of I_{sp}/discharge voltage operation. To address this requirement Busek designed and fabricated a high power hollow cathode, designated BHC-500. This cathode, pictured in Fig. 3, is an engineering model based on our Low Power Hollow Cathode[5] and is designed to deliver up to 50 Amps. The fundamental operating characteristics and key design elements are similar to the configuration used in extensive NASA life and cycling tests. The cathode is a conventional hollow cathode constructed from a 12.8 —UNITS refractory metal tube and a refractory metal orifice at its discharge tip. The size of the orifice and keeper geometry were based on empirically derived scaling factors.

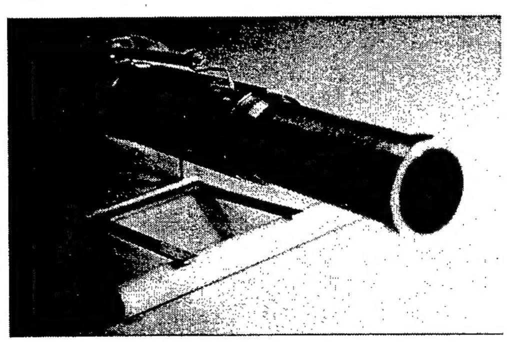

Fig. 3 Photograph of the high power hollow cathode designed and fabricated at Busek

The insert is an impregnated tungsten cylinder with a low work function emitter. A tantalum heater wire, rated for 1450°C, is used to bring the emitter to ignition EMITTING TEMPERATURE? temperature.

The cathode was mounted above the thruster, and no attempt was made to optimize its position or orientation (that work is planned in conjunction with the second generation thruster design). To allow the SURELY IT DOESN'T IGNITE!

cathode to float electrically from the thruster body, ceramic standoffs were used to isolate the cathode from BHT-8000.

Test Facilities and Instrumentation

Busek Co. maintains two of the largest privately owned propulsion test facilities dedicated to testing of Hall effect thrusters. These cryogenic, high pumping speed facilities are essential for maintaining the high vacuum conditions necessary for accurate performance measurements. The facilities are equipped with in-situ diagnostics and performance measurement instrumentation that we use to optimize Hall thruster designs.

italicize ?

For the BHT-8000, thruster testing was performed in our T8 facility shown in Fig. 4. The facility is 2.4 meters in diameter and 5.5 meters in length, constructed from stainless steel. The facility is roughed with a mechanical pump and blower. For test operation the vacuum pumping system consists of two, 22-in. diameter two-stage cryotubs and four large single stage cryosails. An LN_2 baffle is located above the pumping surfaces to prevent overheating during high power testing. The measured total pumping speed of the facility for xenon is approximately 150,000 liters/sec.

Mounted inside the tank is a thrust stand custom-fabricated by Busek of the inverted pendulum style developed by NASA Glenn Research Center.[6] The thrust stand is water cooled, has in-situ calibration, and operator inclination control. The output voltage from a linear variable differential transformer (LVDT), which is proportional to the thrust, is measured and recorded using a strip chart recorder. The experimental procedure used to calibrate the thrust stand prior to and post experiment is similar to that described by Haag.[6]

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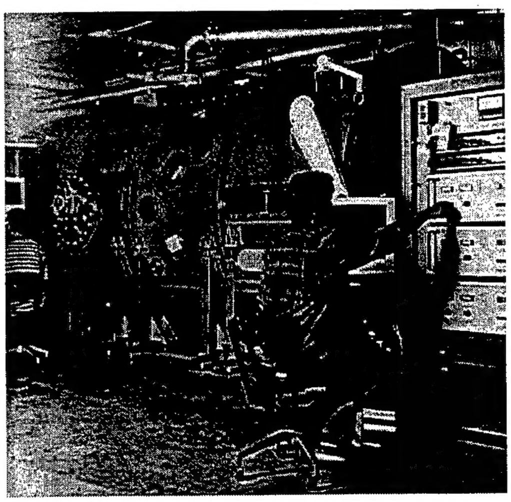


Fig. 4 The T8 vacuum test facility at Busek

The propellant was supplied to the thruster and cathode through commercially available mass flow controllers, calibrated for xenon. In addition, we also conduct periodic calibrations using an in-house designed flow calibration set-up that uses both constant pressure and constant volume techniques. These methods yield calibration curves that are within 5% of each other. Accuracy of the UNIT flowmeters are <1% according to the manufacturer.

Tank pressure is measured using a Granville-Philips ion gauge calibrated for xenon.

The propellant used was research grade xenon having a purity of 99.9995.

BHT-8000 Performance Summary

The BHT-8000 baseline testing evaluated the performance of the thruster over a range of input power, propellant mass flowrate, and discharge voltage. The propellant flow rate to the hollow cathode was adjusted to 5 - 10% of the mass flow to the anode. The electrical configuration is shown in the schematic of Fig. 5. For these tests the thruster body was grounded and the cathode allowed to float. Commercially available power supplies were used to operate the discharge, cathode heater and keeper and all magnets. The facility pressure was, depending on the total flow rate, between $1x10^{-5}$ Torr and $6x10^{-5}$ Torr. No correction for the effects of facility background xenon pressure are included in the data presented.

Table 2 summarizes the results of the performance testing. Shown in the table are data for the thruster operated from 2 - 10 kW power input at 300 and 400 volts discharge. Both the calculated I_{sp} and efficiency do not include the flow rate to the cathode. As shown the thruster is a high performance accelerator. It operates at high efficiency over a very wide throttle range. A photograph of the thruster installed and operating inside the vacuum test chamber is shown in Fig. 6.

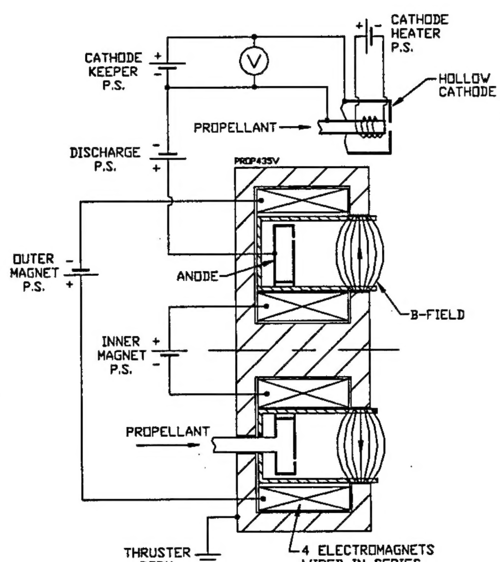


Fig. 5 Electrical schematic for the BHT-8000 testing

Table 2
8 kW Thruster Performance

Power, kW	*2000*	*4000*	*6000*	*8000*	*10,000*
Discharge Voltage	300	300	300	300	
Isp, sec	1658	1895	1946	2024	
η, %	53.6	62.9	61.4	63.4	
Thrust, mN	131.2	269.7	388.5	512	
Discharge Voltage	400	400	400	400	400
Isp, sec	1967	2202	2235	2321	2396
η, %	56.7	65.4	62.3	63.6	66.6
Thrust, mN	117.6	242.2	342.8	449.7	571.3

-Baseline configuration, inner/outer magnet coilsindependently powered

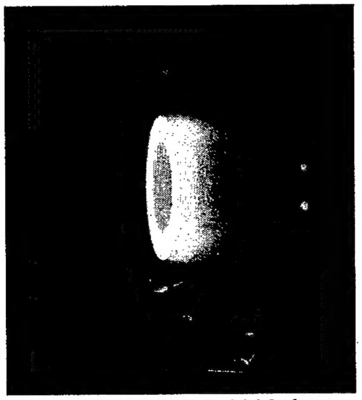


Fig. 6 Photograph of BHT-8000 thruster firing

Analysis and Discussion

The plasma behavior downstream of a thruster exit plane has a significant effect on its performance regardless of the thruster size and type. When the ion beam exiting the thruster forms a sharply defined luminescent zone (on the thruster axis of symmetry), its performance increases. We call this zone a jet or a jet mode of operation. It, along with a simple analytical model of the thruster performance, will be discussed in the next section.

The Jet Mode and Two Parameter Performance Model

The ideal versus actual Hall thruster behavior at a constant input power is shown in Fig. 7. Without losses, the thrust (T) should continuously increase with decreasing Isp. Experimental data however indicate a non-ideal thruster behavior where at some Isp the slope of the curve (dT/dI_{sp}) reverses

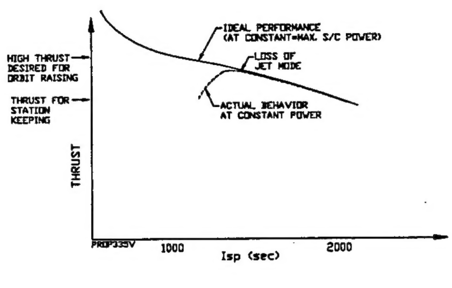


Fig. 7 Idealized versus actual behavior of Hall thrusters at constant input power

The point of reversal generally coincides with the loss of jet mode. To illustrate what is meant by "jet mode," we show in Fig. 8 two photos of a thruster operating at a constant power but different voltage and mass flow (different Isp). A highly luminescent central jet is clearly visible in the left photo and absent in the right hand photo. Disappearance of the central jet coincides with a steep drop in measured thrust which is identified in Fig. 7 as the "loss of jet mode." Discharge voltage has the strongest influence on the point of transition which is also affected by magnetic field magnitude and distribution, mass flow rate and very importantly the test tank pressure.

In order to understand the physical phenomena of the jet we constructed a simple mathematical model that contains enough physics to represent the situation but remains analytically transparent to enhance understanding of the functional relationships. Therefore, we developed a thruster performance model that relies on two easily understandable parameters. One is the flux of cathode electrons that enter the thruster (I_{ee}) to ionize the propellant normalized by the total discharge current ($i = I_{ee}/I_{dis}$) which we illustrate in Fig. 9, and the other parameter is the energy (voltage) loss during the ionization and acceleration process. This loss, labeled ΔV_{ttl}, is composed of all voltage drops that do not create thrust and can be written as

$$\Delta V_{ttl} = \Delta V_c + \Delta V_A + \Delta V_{pb} + \Delta V_w + N\varepsilon_i ..... \quad [5]$$

where ΔV_c and ΔV_A are the cathode and anode voltage drops, the ΔV_{pb} is the voltage dropped in the plasma bridge between the thruster exit and the cathode, ΔV_w is wall losses, and $N\varepsilon_i$ is some multiple of the propellant ionization potential. (Note that ΔV_A could be either negative or positive depending on the current density, electron thermal speed and area of the anode). Thus the discharge voltage V_{dis} can be written as

$$V_{dis} = V_{acc} + \Delta V_{ttl} \quad [6]$$

what? (voltage?)

where V_{acc} is the actual accelerating and hence the useful part of the applied voltage. Typical ΔV_{ttl} is 60 to 80 volts which is about the discharge voltage when the applied magnetic field is zero. The magnitude of I_{ee} (or i) is dictated by how many cathode electrons it takes to produce the total discharge current. As shown in Fig. 9, the ionization process is ideally a chain reaction starting with one cathode (primary) electron, which through a collision with a neutral propellant atom produces an extra electron that in turn produces new electrons etc. If we could arrange things in such a way that each electron emerges from an ionizing collision with near zero energy, is then accelerated by the applied voltage to ε_i and collides again to produce the another electron, then one cathode electron could produce N plasma electrons where N is given by

$$N \approx \frac{V_{dis}}{\varepsilon_i} \approx \frac{300}{12} = 25$$

and therefore

$$\left(\frac{I_{ee}}{I_{dis}}\right) = 2^{-25} \approx 0$$

Under these ideal conditions there are no electron losses (inelastic collisions and wall collisions) leading to a high efficiency thruster.

In reality, each cathode electron produces 4 to 8 propellant electrons (2 to 4 ions) because the typical experimentally demonstrated value of the primary electron loss parameter (i) for multi kW thrusters is about 0.2.

$$i = \frac{I_{ee}}{I_{dis}} = 0.2 = 2^{-N} \Rightarrow N = 2.3$$

Armed with this discussion we can now express the thrust (T), I_{sp} and efficiency (η) in terms of discharge power P_{dis} , and the two loss parameters, i and ΔV_{ttl}

$$T = \dot{m}_t < u > \cong \dot{m}_i u_i \cong \left(\frac{2P_{dis}}{I_{sp}}\right) \frac{k_1(1-2i)}{1+\left(\frac{k_1 \Delta u_i}{I_{sp}}\right)^2} \qquad [7]$$

$$I_{sp} = \frac{T}{\dot{m}_t g_o} \cong \frac{\dot{m}_i u_i}{\dot{m}_t g_o} \cong k_1(1-i)\sqrt{\frac{2q(V_{dis}-\Delta V_{ttl})}{m_i}} \qquad [8]$$

$$\eta = \frac{\frac{1}{2}\dot{m}_i u_i^2}{P_{dis}} \cong (1-i)\left(1-\frac{\Delta V_{ttl}}{V_{dis}}\right) \cong \frac{1-i}{1+\left(\frac{k_1 \Delta u_i}{I_{sp}}\right)^2} \qquad [9]$$

where $k_1 = \left(\frac{I_{dis}}{\dot{m}_t g_o}\right)\left(\frac{m_i}{q}\right) \cong \text{constant} \approx 0.139$ for Xe,

$\Delta u_i = \sqrt{\frac{2q\Delta V_{ttl}}{m_i}}$ = ion velocity deficit due to ΔV_{ttl} loss and

$P_{dis}=I_{dis}V_{dis}=$ applied power, $g_o=9.81 m/sec^2$, $\dot{m}_t$ = total mass flow.

The expression for thrust (Eq.[7]), is not a monotonic function of I_{sp}, but has a maxima dependant on ΔV_{ttl} and i. The maximum occurs when $k_1\Delta u_i/I_{sp}=1$. It means, that every thruster depending on its losses has an I_{sp} at which it delivers maximum thrust. This maximum thrust specific impulse (I_{sp}*) can be expressed as

$$I_{sp}{*} = k_1\Delta u_i = \frac{2\Delta P}{\Delta T g_0} = \frac{2 I_{dis}\Delta V_{ttl}}{g_o \dot{m}_i \Delta u_i} \qquad [10]$$

Thus the maximum thrust I_{sp}, is determined by the ratio of power loss (ΔP) and the thrust loss (ΔT), both of which are functions of ΔV_{ttl} but not i.

Clearly, minimizing ΔV_{ttl} and i leads to the highest thrust and efficiency and small ΔV_{ttl} extends I_{sp}* to a lower value.

Experimental data from the BHT-8000 thruster operated at constant power over greater than a factor of two in Isp (corresponding to a discharge voltage from 100-400 volts) is plotted in Figs. 10 and 11. Input power was varied at 2, 4, 6 and 8 kW. Theoretical curves (Eqs. [7] and [9]) are superimposed onto the experimental data. It illustrates the good agreement between the model and our experimental data. The assumed values of i and ΔV are 0.18 and 50 volts, respectively for the 4, 6 and 8 kW data. A better fit to the 2 kW data was obtained when the i and ΔV terms were adjusted to 0.25 and 30 V.

It should be noted that for Isp<1200 sec, the predicted drop off in performance is slower than experimentally observed in other Busek thrusters. This is due to two factors. The first is that ΔV_{ttl} and i are not independent from each other as the model assumes. The second is that when the thruster falls out of jet mode, the performance drops in a step like fashion which probably means step-like increase in ΔV_{ttl}. We believe as illustrated in Fig. 12, that the jet serves as a low resistance path for electrons (electron highway) from the cathode to the thruster. When the jet disappears, it abruptly increases ΔV_{ttl} with corresponding drop in thrust.

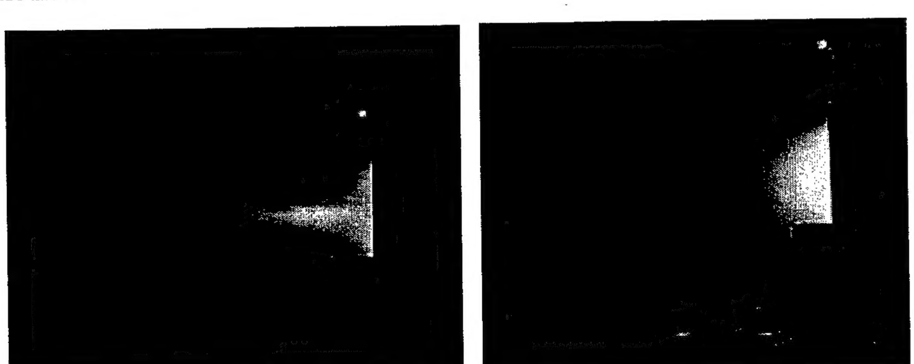
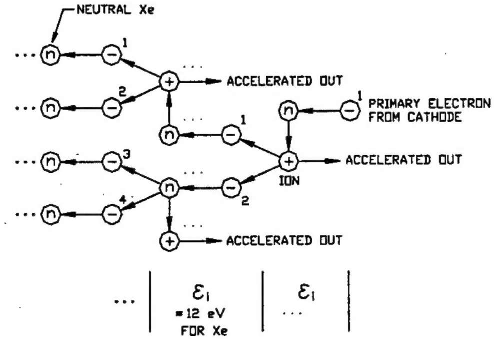


Fig. 8 Typical Busek Hall thruster operation at constant input power (left) operating in jet mode and (right) operating out of jet mode



One Cathode electron results in 2 electrons in first collision, in 2[nd], 8 in 3[rd] ....

$$N \approx \frac{V_{dis}}{\varepsilon_I} \approx \frac{300}{12} = 25$$

$$\Rightarrow \left(\frac{I_{ee}}{I_{dis}}\right)_{\min} = 2^{-25} \approx 0$$

$$\left(\frac{I_{ee}}{I_{dis}}\right)_{Typical} = 0.15 = 2^{-N} \Rightarrow N = 2.74$$

⇒On the average a cathode electron produces 4 to 8 propellant electrons (2 to 4 ions)

Fig. 9 Ionization process in a Hall thruster

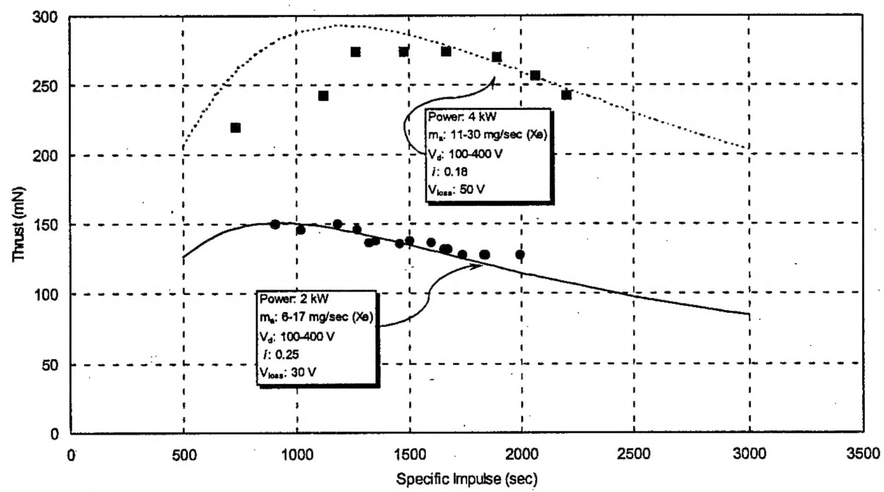


Fig. 10 Thrust vs. Isp for the BHT-8000 operating at 2 and 4 kW input power. The experimental data is compared to our two parameter model

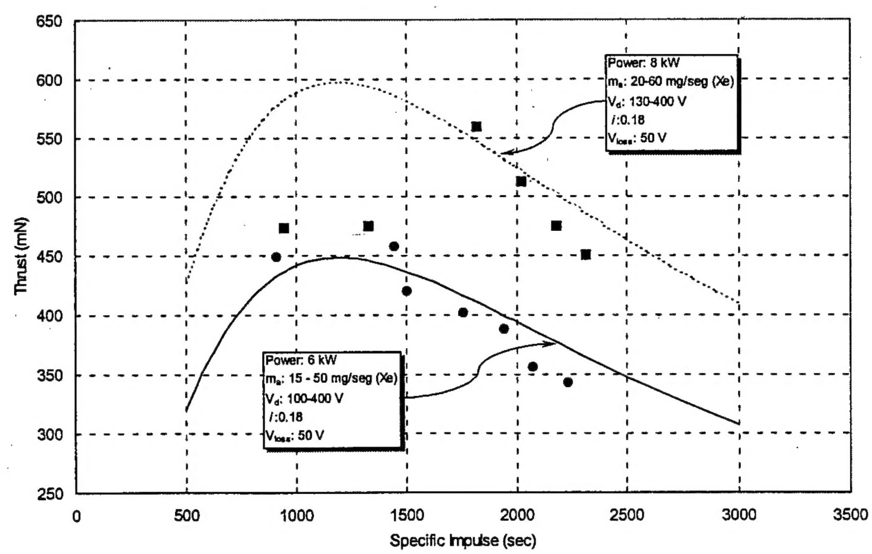


Fig. 11 Thrust vs. Isp for the BHT-8000 operating at 6 and 8 kW input power. The experimental data is compared to our two parameter model

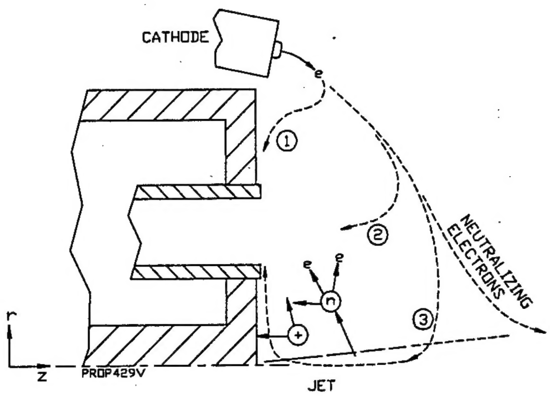


Fig. 12 Preferred electron path from cathode to thruster exit is #3. Path #1 is unlikely because of low local density of neutrals and because the electrons would have to cross strong B field lines as they would following path #2

Conclusions

A high power (8 kW) Hall thruster was successfully designed, constructed and tested in our vacuum test facility. The measured performance in its baseline configuration exceeded the predicted performance and compares favorably with thrusters of similar size. Our simple analytical model, developed to predict Hall thruster performance, given two loss parameters (voltage and electron loss) correctly predicts the high power thruster performance. This further demonstrates the applicability of the model to all sizes of thruster regardless of the internal design features.

The results obtained further substantiate the strong effect on thruster performance of the highly luminescent central jet within the thruster discharge plume. We believe the plasma inside the jet is a highly conductive region and serves to provide a preferential path for electrons to couple with the plasma. Better coupling between the cathode and the thruster improves the performance by lowering the voltage loss.

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